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SUSTAINABLE FABA BEAN (*Vicia faba* L.) USING VERMICOMPOST AND NITROGEN-FIXING BACTERIA (*Rhizobium* sp.)

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ABSTRACT: This study explores the combined effects of vermicompost application and Rhizobium inoculation on faba bean (*Vicia faba* L.) growth, nodulation, and yield over two successive winter seasons (2022/23 and 2023/24) in sandy soil at El-khatttara region, Sharkia Governorate, Egypt. Four levels of vermicompost (0, 1.5, 3.0, and 4.5 ton/fad.) and three inoculation treatments (uninoculated, *Rhizobium tropici*, and *Rhizobium gallicum*) were evaluated using a randomized complete block design in split plot arrangement with three replicates. Results demonstrated that the highest vermicompost level (4.5 ton/fad.) significantly increased the number of nodules per plant (up to 95.19 nodules on average) and dry nodule weight (up to 2.14 g in the second season). *Rhizobium tropici* inoculation outperformed *R. gallicum*, with a 17.45% higher nodulation response and improved nitrogen fixation. Plant height increased by 41.19%, and branchs number per plant peaked at 5.31 under the combined application of 4.5 ton/fad., vermicompost and *R. tropici* inoculation. Yield components showed remarkable improvements: the highest average of number of pods (39.65 pods/plant), seeds per pod (5.90), and 100-seed weight (92.43 g) were achieved under the same treatment combination. Biological yield reached 5.98 ton/fad., while seed and straw yields were 2.52 and 2.36 ton/fad, respectively, representing over a 30% increase compared to control treatment. Total nitrogen uptake and protein yield were also maximized at 132.5 kg/fad and 431.39 kg/fad., respectively, under these treatment. The study highlights the synergistic benefits of combining organic amendments and microbial inoculants, promoting sustainable faba bean production with enhanced nitrogen uptake, protein content and soil fertility.

Key words: Faba bean (*Vicia faba* L.), vermicompost, rhizobium inoculation, nitrogen fixation, yield components, sustainable agriculture.

INTRODUCTION

Faba bean (*Vicia faba* L.) is a leguminous crop that plays a significant role in the Egyptian agricultural sector, and serves as a source of income for many farmers. It is cultivated primarily for its edible seeds, which are rich in protein content, vitamins, and minerals.

The importance of faba bean extends beyond its nutritional value; it also contributes to soil fertility through nitrogen fixation, making it an essential component of sustainable agricultural practices. The crop is well-suited to the Egyptian climate and can be grown in various soil types, although it thrives best in fertile soils. Its cultivation supports food security and provides employment opportunities in rural areas. According to the Food and Agriculture Organization (FAO), the harvested area for faba beans in Egypt was approximately 123,480 hectares with a production volume reaching around 2 billion ton (**FAO, 2022**). This represents a slight increase compared to previous years due to improved agricultural practices and increased demand for legumes. Additionally, Egypt's trade dynamics concerning faba beans indicate that while the country produces a significant quantity domestically, it also engages in international trade. As per recent data from the Central Agency for Public Mobilization and Statistics (CAPMAS), Egypt imported about 50,000 ton of faba beans while exporting approximately 30,000 ton during the same period.

The sustainability of faba bean production is crucial given its role in food security and economic stability. With sandy soils prevalent in

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many regions of Egypt, there exists an opportunity to expand the cultivation of faba beans by employing proper agricultural practices tailored for these soil types. Sandy soils are often lack in nutrients; thus, enhancing their fertility through organic amendments like vermicompost can significantly improve yield outcomes.

Utilizing vermicompost aligns with sustainable agriculture principles by reducing reliance on chemical fertilizers and improving soil health over time. Its application enhances growth rates and yields in crops like faba beans, as it acts as an organic fertilizer produced through the decomposition process facilitated by earthworms. Vermicompost serves as an effective soil amendment by improving soil structure, increasing nutrient content, enhancing microbial activity, and promoting water retention in sandy soils (**El-Naggar *et al*., 2020**). Studies showed that applying vermicompost significantly increases plant height and the biomass yield in *Vicia faba* (**Abd El-Monem *et al*., 2019**). Additionally, vermicompost application leads to higher nitrogen content in both leaves and seeds compared to conventional fertilizers, while also improving microbial diversity within the rhizosphere (**Hassan *et al*., 2021**). Plants treated with vermicompost demonstrate greater resistance to common fungal diseases affecting legumes, indicating a protective effect in addition to nutrient benefits (**Farag *et al*., 2022**). Incorporating vermicompost into sandy soils is also associated with a notable increase in seed yield per hectare (**Ghanem *et al*., 2021**). Overall, vermicomposting contributes positively to sustainable agriculture by enhancing crop productivity and promoting healthier soils (**Mohamed *et al*., 2023**).

Nitrogen-fixing bacteria (NFB) play a crucial role in enhancing the growth and productivity of *Vicia faba* by converting atmospheric nitrogen into plant-usable forms, thus reducing dependence on synthetic fertilizers. Inoculating *Vicia faba* seeds with nitrogen-fixing bacteria can result in up to 25% higher yields than non-inoculated controls (**Ali *et al*., 2018**). Inoculated plants has improved protein content within their seeds (**Khedher *et al*., 2019**). Furthermore, inoculation leads to enhanced root nodulation, which directly correlates with better nutrient uptake (**El-Sharkawy *et al*., 2020**). This technique also increases resilience under drought conditions, allowing plants to perform better under environmental stress (**Zaki *et al*., 2021**). Beyond productivity gains, inoculation positively influences soil microbial communities, benefiting overall soil health (**Abdel-Moneim *et al*., 2022**). A recent cost-benefit analysis concluded that utilizing nitrogen-fixing bacteria can reduce input costs and maximize output efficiency for farmers cultivating *Vicia faba* (**Soliman *et al.*, 2023**).

Rhizobium is a bacterial genus known for its ability to fix atmospheric nitrogen in symbiosis with leguminous plants, including faba beans (*Vicia faba* L.). The process of nitrogen fixation is crucial for enhancing soil fertility and promoting plant growth. Various strains of Rhizobium have been identified that specifically associate with faba beans; among them, R. *tropici* and R. *gallicum* which are two of the most common rhizobia associated with legumes, including faba beans through a potential contribution in roots nodulation where nitrogen is fixed while living symbiotically on plant roots. *R. gallicum* exhibits a high level of genetic diversity, allowing it to adapt to different soil types and climates. Also, *R. gallicum* can form effective nodules that significantly contribute to nitrogen fixation (**Zahran, 1999**). These information highlight the importance of these bacteria in sustainable agriculture practice and understanding which strain is more effective in improving crop yields and soil health through enhanced nitrogen availability.

The current study aimed at assessing the influence of incorporating four vermicompost levels and three inoculation treatments by symbiotic nitrogen fixing bacteria on growth, yield and quality of faba bean crop (*Vicia faba* L.).

MATERIALS AND METHODS

Experimental Field Location and Aim of Research

On field trail was carried out during the two successive winter seasons of 2022/2023 and 2023/2024 in the Experimental Farm, Faculty of Agric., Zagazig Univ., Egypt, which is located in El-Khattara region, Sharqia Governorate, Egypt (30°39'54.2"N 31°53'05.2"E) to investigate the influence of four vermicompost levels (0, 1.5, 3 and 4.5 ton/fad.) and three inoculation treatments by symbiotic nitrogen fixing bacteria (check “control”, inoculation by singly each of *Rhizobium tropici* and *Rhizobium gallicum*) on growth, yield and quality of faba bean (*Vicia faba* L.). The combinations of the 4 vermicompost levels and the 3 *Rhizobium* inoculation treatments are listed in Table 1.

Statistical layout

Split plot in a randomized complete block design in three replicates was used to carry out the study. Four vermicompost levels were assigned to the main plots; sub-plots were devoted to 3 inoculation treatments. Each sub-plot area was 10 m2(2.5×4 m), which included 3 rows, 80 cm apart. A distance of 2 m among plots was left to fade the overlapping of treatments.

Soil preparation and sampling

During soil preparation, soil samples from the upper 30 cm depth were taken to assess both physical and chemical properties of the experimental site soil which were as follows: 88.4% sand, 4.2% silt, 7.4% clay, pH 7.4, 0.5% organic matter, EC 0.8 ds/m, available N 25 ppm, available P 10.2 ppm and available K_2O 100 ppm. Soil parameters were valued as described by **Jackson (1958) and Lindsay and Norvell (1978)**.

Vermicompost Addition

Plots were prepared by plowing twice and leveling, the phosphorus fertilizer as mono calcium superphosphate (15.5% P_2O_5) was broadcasted at 200 kg fertilizer/fad (fad, 4200 m^2). After preparing the plots, Vermicompost was buried at 15 cm depth from soil surface in longitudinal grooves according to levels distributed as per the sowing map and were completely covered with the soil. Chemical analysis of vermicompost is listed in Table 2.

Bacterial Inoculation

The bacterial inoculation to the seeds was performed at 10 g of the inoculants containing 150 alive cells/g); later, inoculated seeds were air dried for 15 minutes under shadow, directly, before manual sowing. Inoculants were obtained from the Agricultural Microbiology Research, Soils, Water and Environment Res. Institute, Agricultural Research Center (ARC), Egypt.

Agricultural Practices

Faba bean seeds (Nubaria 1 cv.) were obtained from the Agricultural Research Center (ARC), Giza, Egypt. Sowing was carried out on Nov. 15^{th} in both seasons in hills at 3 cm depth at seeding rate of 50 kg/fad. (fad., 4200 m^2) as recommended in sandy soil achieving a plant density of 138600 plant/fad (33 plants/m^2). All agricultural practices recommended for faba bean crop tillage were done. Weed control was performed trice by weeds hand uprooting. Potassium fertilizer as potassium sulfate (48% K_2O) was added during soil preparation at 48 kg/fad., while a unique dose of chemical nitrogenous fertilizer was fertigated as Urea (46%) 15 days after sowing (DAS). Irrigation was drip system with an inter drip spacing of 20 cm and the total seasonal consumptive use of water was amounted to approximately 2500 m^3/fad. Plants were manually harvested 145 DAS. Plants were set to air dry for 1 week before its threshing and winnowing.

Recorded Data

The number of nodules was counted manually after flowering through uprooting 10 plants carefully to avoid nodule loss and the nodules on the root systems of selected plants were counted, following the method described by **Vincent (1970)**. Bacterial nodules were collected from each plant, dried at 70°C to constant weight, and then weighed. This process followed the procedure outlined by **Peoples and Turner (1989)** for nodule weight measurement. Plant height was measured from the base to the apex 10 plants using a ruler at maturity for 10 plants. Measurements were taken as per the standard method described by **Misbahuzzaman *et al*. (2004)**. Number of branches per plant was counted at maturity, following the method used by **Hamdi *et al.* (2019)** in legume studies. Pods per plant were counted at harvest for each selected plant, following the procedure by **Saxena and Singh (1987)** for pulse crops. Seeds in each pod were counted manually. This was done for a subset of plants to provide an average, as outlined by **Saxena and Singh (1987)**. A random sample of 100 seeds was weighed using a precision balance to determine average seed weight. This method follows guidelines by **FAO (1980)**. Total above-ground biomass of each plant

Table 1. Combinations of vermicompost levels and *Rhizobium* inoculations

Number	Combination
1	0 VC/fad + non-inoculated
2	0 VC/fad + R. *tropici*
3	0 VC/fad + R. *gallicum*
4	1.5 ton VC/fad + non-inoculated
5	1.5 ton VC/fad + R. *tropici*
6	1.5 ton VC/fad + R. *gallicum*
7	3 ton VC/fad + non-inoculated
8	3 ton VC/fad + R. *tropici*
9	3 ton VC/fad + R. *gallicum*
10	4.5 ton VC/fad + non-inoculated
11	4.5 ton VC/fad + R. *tropici*
12	4.5 ton VC/fad + R. *gallicum*

VC is vermicompost

Table 2. Chemical compounding of vermicompost

Property	UNIT	VALUE
PH	-	6.5-7.5
EC	DSM^{-1}	3.5
Total N	%	3
Total P	%	0.5-1
Total K	%	0.7-1
Total CA	%	2-3
Total MG	%	2
Organic carbon	%	15-25
C/N ratio	-	1:15
Water holding capacity (WHC)	%	95
Organic matter	%	33

was harvested, dried, and weighed to determine biological yield, following standard field protocol as outlined by **Donald and Hamblin (1976)**. Seed yield (ton/fad.) was measured at harvest and weighed after drying to ensure moisture content consistency, as per protocols by **Gomez and Gomez (1984)**. Straw yield (ton/fad.) was calculated as the difference between biological yield and seed yield, following the method by **Singh *et al*. (1997)**. Harvest index was calculated using the formula: Harvest Index = (Seed Yield/ Biological Yield)× 100, as outlined in **Beadle (1993)**. Nitrogen content in seeds and straw (%) was determined using the Kjeldahl method, as described by **Bremner (1996)**, a standard method for nitrogen analysis. Nitrogen uptake in seeds (kg/fad.) and in straw (kg/fad) was calculated by multiplying the nitrogen content by the yield of seeds and straw, respectively. This method was based on procedures described by **Black (1965)**. Total nitrogen uptake (kg/fad) was the sum of nitrogen uptake/content in seeds and straw, as outlined by **Bremner (1996)**. Protein yield (kg/ fad.) was calculated by multiplying the nitrogen content in seeds by the protein conversion factor (6.25), as described by Kjeldahl protocol in **Black (1965)**.

Statistical Analysis

An analysis of variance was conducted for the studied traits for each season separately. The least significant difference (LSD) was used to compare the averages. Data recorded from each plot were subjected to the analysis of variance (ANOVA) of the Split plot in a randomized complete block design according to **Donald and Hamblin (1978)** using COSTAT-Statistics Software 6.400 package as described by **Cardinali and Nason (2013).**

RESULTS AND DISCUSSION

Nodulation and Plant Growth

Results presented in Table 3 affirm that there were significant effects of vermicompost additionand *Rhizobium* inoculation treatments on No. of nodules/plant and its dry weight as well as plant height and No. of branches/plant in both seasons and combined analysis. As well, results in Table 4 show the effect of the interaction between vermicompost levels and rhizobium inoculation treatments.

Number of Bacterial Nodules/plant

In terms of vermicompost levels (Table 3), No. of bacterial nodules when vermicompost is not added recorded average counts of 26.26 and 29.36 in the first and second seasons, respectively with a combined average of 27.81.

Supplies of 1.5 ton vermicompost/fad increased sensibly nodule number/plant to 53.67 and 60.12 in the 1st and the 2nd seasons, orderly. Further enhancement in nodulation was achieved ascribed to raising the supplies of the vermicompost to 3 ton/fad, Accordingly, nodules number/plant recorded more increments and valued 75.09 and 82.51 in the 1st and the 2nd seasons, in the same order. More supplies with the vermicompost up to 4.5 ton/fad., were correlated with marked increase in nodule No./ plant, recording the uppermost value (95.19) in the pooled analysis.

Results of both seasons and their pooled analysis regarding Rhizobium strains inoculation displayed that inoculated faba bean plants outnumbered the non-inoculated ones in nodule number/plant. Eke, plants inoculated with the *R. tropici* strain had more nodules/plant (73.85) than those inoculated with the *R. gallicum* strain (62.88), with relative increases as much as 17.45% (combined results).

Interaction effects (Table 4) show that, without *Rhizobium*, nodules ranged from 23.48 at 0 ton/fad to 80.56 at 4.5 ton/fad. With *Rhizobium gallicum* (R_1), nodules increased from 25.66 at zero ton/fad., to 88.03 at 4.5 ton/fad.

The uppermost nodules number/plant (101.72 and 115.67) was the resultant of the interaction effect between the highest level supply of vermicompost (4.5 ton/fad) and the inoculant *R. tropici*, in the 1st and 2nd seasons, orderly, whilst the fewest nodule number/plant (23.48 and 25.81) was obtained under the effect of the interaction between no supply of vermicompost and uninoculation treatment.

These results suggest a positive impact of vermicompost on nodulation in faba bean plants, taking into consideration that each increase in vermicompost application contributing to higher nodulation across seasons. Additionally, the inoculation treatments significantly amplified these effects. *R. tropici*, in particular, showed the most substantial increase, likely due to its compatibility with the host plant's root system, suggesting it may be more effective in enhancing nitrogen fixation compared to *R. gallicum* or uninoculation. Overall, both higher vermicompost levels and specific *Rhizobium* inoculations are avail for maximizing nodulation, which is crucial for improving faba bean growth and yield potential. These results hold true with what was reported by **Abd-Alla and El-Enany (2009)** as well as **Farooq *et al.* (2012)**.

Nodules Dry Weight (g)

According to the results in Table 3, in the first season, the nodules dry weight at zero ton vermicompost/fad., averaged 0.94 g, increasing to 1.55 g at supply of 1.5 ton/fad, and reaching 1.95 g at supply of 4.5 ton vermicompost/fad. In the second season, weights increased slightly to 1.04 g, 1.71 g, and 2.14 g for the same treatments, with combined seasonal averages of 0.99 g, 1.63 g, and 2.05 g, respectively.

Interaction effects (Table 4) indicate that each increase in vermicompost supplies under the three inoculation treatments was conjoined with operative increases in nodules dry weight (g/plant) in both seasons. On the other direction of the interaction, results of both seasons showed that inoculation with the strain *R. tropici* was more effective in increasing the weight of nodules/plant, whatever the level of vermicompost supplies. The heaviest weight of nodules/ plant (2.14 and 2.35 g) was the outturn of the interaction effect of $V_4 \times R_2$ in the 1st and 2nd season, respectively. Meanwhile, the lightest weight of nodules (0.99 and 1.10 g) was the outcome of the interaction effect of $V_1 \times R_0$ in the 1st and 2nd seasons, orderly.

These findings suggest that increasing vermicompost levels enhances nodules' dry weight, contributing positively to plant biomass. The presence of *R. tropici* maximized dry weight across all vermicompost levels, indicating it may improve nutrient uptake and biomass accumulation more effectively than *R. gallicum*. This response underscores the benefit of combining higher vermicompost levels with effective *Rhizobium* strains for better nitrogen assimilation in faba beans. These results go in line with **Badawy and El-Sayed (2011), Hamdi *et al.* (2019) and Ahmed *et al*. (2020)**. In addition to

Plant height (cm)

Faba bean plant height was affected by supplying levels of vermicompost alongside Rhizobium strains inoculation (Table 3). The tallest faba bean plants (136.86 and 119.71 cm) was the result of the vermicompost supply at 4.5 ton/fad., in the 1st and 2nd seasons in the same order (pooled results). The relative increase in the faba bean height due to the application of V_4 treatment, comparably with V_1, V_2 and V_3 treatments, amounted as 41.19, 32.14 and 24.24% (combined results). Allusive to the influence of the inoculation by Rhizobium strains, results in Table 3 exhibited that whatever the Rhizobium

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Table 3. Number of nodules/plant, nodules dry weight/plant, plant height and number of branches/ plant of faba bean as affected by vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Treatment	Number of nodules/plant			Nodules dry weight/plant (g)			Plant height (cm)			No. of branches/plant		
	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.
Vermicompost level (V)												
Without supply (V_1)	26.26 d	29.36 d	**27.81 d**	0.94 d	1.04 d	**0.99 d**	91.86 d	101.99 d	**96.93 d**	3.76 c	4.15 c	**3.96 d**
1.5 ton/fad (V_2)	53.67 c	60.12 c	**56.89 c**	1.20 c	1.34 c	**1.27 c**	98.06 c	109.08 c	**103.57 c**	3.81 c	4.20 c	**4.01 c**
3 ton/fad (V_3)	75.09 b	82.51 b	**78.80 b**	1.55 b	1.71 b	**1.63 b**	103.82 b	116.13 b	**109.97 b**	4.00 b	4.49 b	**4.25 b**
4.5 ton/fad (V_4)	90.10 a	100.29 a	**95.19 a**	1.95 a	2.14 a	**2.05 a**	129.46 a	144.26 a	**136.86 a**	4.49 a	4.93 a	**4.71 a**
F.test	*	*	*	*	*	*	*	*	*	*	*	*
Rhizobium strains inoculation												
Without inoculation (R_0)	54.79 c	59.83 c	**57.31 c**	1.49 c	1.64 b	**1.57 b**	91.79 b	101.93 b	**96.86 b**	3.8 b	4.18 b	**3.99 b**
R. gallicum (R_1)	59.87 b	65.88 b	**62.88 b**	1.19 b	1.34 c	**1.27 c**	112.71 a	125.16 a	**118.94 a**	3.8 b	4.19 b	**3.00 b**
R. tropici (R_2)	69.18 a	78.51 a	**73.85 a**	1.55 a	1.70 a	**1.63 a**	112.90 a	126.51 a	**119.71 a**	4.45 a	4.96 a	**4.71 a**
F.test	*	*	*	*	*	*	*	*	*	*	*	*
Interaction (V × R)	*	*	*	*	*	*	*	*	*	*	*	*

* denotes Significant at 5% probability level

Table 4. Number of nodules/plant, nodules dry weight/plant, plant height and number of branches/ plant of faba bean as affected by the interaction between vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Trait	Number of nodules/plant				Nodules dry weight/plant (g)				Plant height (cm)				No. of branches/plant			
VC levels	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4
Rhizobium	**1st season**															
R_0	23.48 j	47.99 h	67.14 e	80.56 c	0.99 h	1.64 c	1.27 e	2.06 b	79.70 g	85.07 f	90.07 e	112.32 b	3.56 g	3.61 f	3.79 e	4.25 c
R_1	25.66 j	52.44 g	73.36 d	88.03 b	0.79 i	1.31 d	1.01 g	1.65 c	97.86 d	104.46 c	110.60 b	137.92 a	3.56 g	3.61 f	3.79 e	4.25 c
R_2	29.65 i	60.59 f	84.77 b	101.72 a	1.03 g	1.7 f	1.32 d	2.14 a	98.02 d	104.64 c	110.79 b	138.15 a	4.17 d	4.22 c	4.43 b	4.98 a
	2nd season															
R_0	25.81 k	52.84 h	72.52 e	88.15 c	1.1 h	1.81 d	1.42 f	2.26 b	88.2 g	94.34 f	100.43 e	124.76 b	3.91h	3.95 g	4.23 e	4.64 d
R_1	28.42 j	58.19 g	79.86 d	97.06 b	0.9 i	1.48 e	1.16 g	1.85 c	108.31 d	115.84 c	123.32 b	153.20 a	3.92 h	3.96 f	4.24 e	4.65 d
R_2	33.86 i	69.34 f	95.16 b	115.67 a	1.14 g	1.88 c	1.47 e	2.35 a	109.48 d	117.09 c	124.65 b	154.85 a	4.64 d	4.69 c	5.02 b	5.51 a

VC levels are vermicompost levels, R_0 is uninoculation, R_1 is *Rhizobium gallicum*, R_2 is *Rhizobium tropici*, V_1 =0 ton/fad, V_2 =1.5 ton/fad, V_3 =3 ton/fad and V4 = 4.5 ton/fad.

Plant height (cm)

Faba bean plant height was affected by supplying levels of vermicompost alongside Rhizobium strains inoculation (Table 3). The tallest faba bean plants (136.86 and 119.71 cm) was the result of the vermicompost supply at 4.5 ton/fad., in the 1st and 2nd seasons in the same order (pooled results). The relative increase in the faba bean height due to the application of V_4 treatment, comparably with V_1, V_2 and V_3 treatments, amounted as 41.19, 32.14 and 24.24% (combined results). Allusive to the influence of the inoculation by Rhizobium strains, results in Table 3 exhibited that whatever the Rhizobium strain used to inoculate faba bean seeds, inoculated plants outgrew uninoculated plants in heights. Faba bean plant height was at par at the two Rhizobium strains, and these results are the assertory in the two seasons and their pooled analysis.

The response of faba bean plant height to the interaction effect between the two factors studied (Table 4) took a resemblance to the effect of the main factors. Accordingly, and regardless of the inoculation treatment, each increase in the vermicompost supply was correlated with operative increases in the plant height. Eke, in the other direction of the interaction, inoculated faba bean plants were taller than those uninoculated ones under the four vermicompost treatments in both seasons.

Plant height demonstrated an upward trend with increased vermicompost application, affirming that organic amendments can stimulate vegetative growth. The notable increase in height with *R. tropici* inoculation implies that this strain may enhance root development and nutrient availability, supporting robust vertical growth. These results suggest that combining higher vermicompost levels with *Rhizobium* strains, particularly *R. tropici*, can improve the structural development of faba bean plants. These results are supported by the reports of **Gupta and Sharma (2007)** which affirmed the role of vermicompost application as an organic amendments in stimulating plant vegetative growth.

Number of Branches/Plant

On the account of the meta-analysis results (Table 3), an increase in branch number/plant was affirmed with each raise in the biofertilizer vermicompost level up to 4.5 ton/fad. Branching of faba bean plants fertilized with the highest vermicompost level outnumbered those plants unfertilized or fertilized with lower levels of vermicompost. Allusive to the effect of the inoculation by Rhizobium strains, results in Table 3 show that branch number/plant of plants inoculated by the *R. tropici* outclass branch numbers in the inoculation treatments R_0 and R_1.

The number of branches per plant improved moderately with higher vermicompost applications, which can promote better canopy development and, consequently, photosynthetic capacity. The most significant increase was seen with *R. tropici* inoculation, suggesting that it may encourage lateral growth and enhance the plant's branching architecture. This enhanced branching, when combined with optimal vermicompost levels, could positively impact overall yield by providing more sites for flower and pod development.

The effect of the interaction between the vermicompost levels supply and the inoculation treatments was analogous to the effect of the main factors under study. So the highest branch numbers/plant (4.98 and 5.31) was the resultant of the combination $V_4 \times R_2$ in the 1st and 2nd seasons, respectively, meantime the lowermost branch number/plant (3.56 and 3.91) was obtained from the interaction effect of the combination $V_1 \times R_0$ in the 1st and the 2nd seasons, respectively.

Yield and Yield Components

Results presented in Tables 5, 6, 7 and 8 show the significant effect of vermicompost addition and Rhizobium inoculation on yield components and final yields and harvest index of faba bean as well as the influence of interaction between the two study factors on the yield component traits.

Number of Pods/Plant

Vermicompost significantly influenced the number of pods per plant across both seasons (Table 5). The highest number of pods/plant was observed with 4.5 ton/fad., (V_4), achieving 36.09 and 39.65 pods/plant in the 1st and 2nd seasons, respectively. In contrast, the control treatment (V_1) had the lowest number of pods, recording 15.67 and 17.60 in the same respective seasons. This represents a remarkable increase of more than 120% under the highest vermicompost level compared to the control.

Rhizobium inoculation showed insignificant differences in the number of pods across both seasons. However, R_2 (*Rhizobium tropici*) produced slightly higher pod numbers (27.09 and 30.15) compared to the un-inoculated control (R_0), which recorded 25.87 and 28.93 pods/ plant in the 1st and 2nd seasons, respectively.

The interaction between vermicompost levels and Rhizobium inoculation was significant. In the 1st season, the combination of $V_4 \times R_2$ produced the highest number of pods/plant (37.30), while $V_1 \times R_1$ showed the lowest number (15.36). Similarly, in the 2nd season, the $V_4 \times R_2$ combination yielded 41.19 pods/plant, significantly outnumber all other combinations.

The increase in pod numbers with higher vermicompost levels reflects enhanced soil fertility and microbial activity, which promote flowering and pod formation. Rhizobium inoculation, particularly with R_2, further amplified these benefits by improving nitrogen availability. The significant interaction highlights the synergistic effects of these treatments in optimizing reproductive development. These results go in line with **Bakry *et al*. (2011)**.

Number of Seeds/Pod

Vermicompost application significantly improved the number of seeds per pod (Table 5). The highest values were recorded at V_4 (5.46 and 5.90 seeds in the 1st and 2nd seasons, respectively). The control treatment (V_1) consistently produced the lowest seed numbers/ pod (4.52 and 5.06 across the two seasons, orderly). *Rhizobium gallicum* (R_1) produced the highest number of seeds/pod (5.10 and 5.59 in the 1st and 2nd seasons, respectively), followed closely by R_2. The uninoculated control (R_0) had the lowest values, demonstrating the importance of inoculation in enhancing seed development.

The interaction between vermicompost and Rhizobium inoculation was not significant for this trait, suggesting that the effects of these factors on seed number/pod were independent.

Higher seed number at elevated vermicompost levels indicate improved nutrient availability, particularly phosphorus and potassium, which are critical for seed set. Rhizobium inoculation, especially with R_1, further supported seed development through enhanced nitrogen fixation, enabling optimal pod filling (**Hussein and Abo Taleb, 2023).**

100-Seed Weight (g)

The results in Table 5 show that seed index was significantly affected by vermicompost levels. V_2 produced the heaviest seeds (85.28 and 92.43 g in the 1st and 2nd seasons, respectively), followed closely by V_4. The lowest weights were recorded in the control (80.18 and 88.30 g). R_1 showed the highest seed weights (85.25 and 93.58 g across the 1st and the 2nd seasons, in order), surpassing R_0 and R_2. This highlights the positive influence of *Rhizobium gallicum* on seed filling.

Significant interaction effects were observed (Table 6). In the first season, the combination of $V_2 \times R_1$ produced the heaviest seeds (87.39 g), while $V_1 \times R_0$ recorded the lightest (79.44 g). In the second season, the combination of $V_4 \times R_1$ yielded the highest seed weight (95.46 g).

Heavier seeds under higher vermicompost levels reflect improved soil organic matter and nutrient availability, enhancing seed filling. The superior performance of R_1 could be attributed to its nitrogen-fixing efficiency and better compatibility with the crop. The interaction results suggest that vermicompost and Rhizobium strains complement each other in improving seed quality. These results are in accordance with **Manasa and Reddy (2019)**.

Biological, Seed and Straw Yield (ton/fad.)

Results presented in Table 7 show that vermicompost treatment V_4 (4.5 ton/fad) consistently achieved the highest biological yields (5.39 and 5.98 ton/fad in the 1st and 2nd seasons, respectively), while V_1 had the lowest (Table 7). The highest seed yield was recorded under V_4 (2.26 and 2.52 ton/fad.), significantly exceeding V_1 (1.72 and 1.92 ton/fad). Straw yield followed a similar trend, with V_4 producing the most (2.12 and 2.36 ton/fad) and V_1 produced the least. R_2 outperformed the other strains in seed and biological yields (5.41 and 2.43 ton/fad combined across the two seasons, orderly). However, R_1 showed slightly higher straw yield than R_2 (Table 7).

Significant interactions were observed. The combination of $V_4 \times R_2$ achieved the highest biological (6.56 ton/fad) and seed yields (2.92 ton/fad.) in the second season. Straw yield was also maximized under $V_4 \times R_1$.

Table 5. Number of pods/plant, number of seeds/pod and 100 seed weight (g) of faba bean as affected by vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Treatment	Number of pods/plant			Number of seeds/pod			100 seed weight (g)		
	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.
Vermicompost level (V)									
Without supply (V_1)	15.67 c	17.60 c	**16.64 c**	4.52 d	5.06 d	**4.79 d**	80.18 d	88.30 c	**84.24 c**
1.5 ton/fad (V_2)	27.01b	29.96 b	**28.49 b**	4.68 c	5.22 c	**4.95 c**	85.74 a	93.88 a	**89.81 a**
3 ton/fad (V_3)	26.08 b	28.90 b	**27.49 b**	4.99 b	5.65 b	**5.32 b**	83.37 c	93.53 a	**88.45 b**
4.5 ton/fad (V_4)	36.09 a	39.65 a	**37.87 a**	5.46 a	5.90 a	**5.68 a**	85.28 b	92.43 b	**88.86 b**
F.test	*	*	*	*	*	*	*	*	*
Rhizobium strains inoculation									
Without inoculation (R_0)	25.87	28.93	**27.40**	4.91 b	5.40 b	**5.16 b**	82.87 c	90.08c	**86.48 c**
R. gallicum (R1)	25.69	28.01	**26.85**	5.10 a	5.59 a	**5.35 a**	85.25 a	93.58 a	**89.42 a**
R. tropici (R2)	27.09	30.15	**28.62**	4.74 c	5.39 b	**5.07 c**	82.81 b	92.44 b	**87.63 b**
F.test	NS	NS	NS	*	*	*	*	*	*
Interaction (V × R)	*	*	*	NS	NS	NS	*	*	*

* denotes Significant at 5% probability level. NS denotes non-significant.

Table 6. Number of pods/plant and 100 seed weight (g) as affected by the interaction between vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Trait	Number of pods/plant				100 seed weight (g)			
VC level	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4
Rhizobium	**1st season**							
R_0	15.47 fg	26.66 d	25.74 de	35.62 b	79.44 f	84.95 c	82.6 d	84.49 c
R_1	15.36 g	26.47 d	25.56 e	35.37 b	81.72 e	87.39 a	84.97 c	86.92 b
R_2	16.20 f	27.92 c	26.96 cd	37.30 a	79.38 f	84.89 c	82.54 d	84.43 c
	2nd season							
R_0	17.55 fg	29.87 d	28.81 de	39.53 b	86.43 i	91.89 e	91.55 e	90.47 f
R_1	16.99 g	28.92 d	27.89 e	38.27 b	89.79 g	95.46 a	95.11 a	93.99 c
R_2	18.29 f	31.13 c	30.03 c	41.19 a	88.69 h	94.30 b	93.95 c	92.84 d

VC levels are vermicompost levels, R0 is un inoculation, R_1 is *Rhizobium gallicum*, R_2 is *Rhizobium tropici*, V_1 =0 ton/fad., V_2 =1.5 ton/fad., V_3 =3 ton/fad and V4 = 4.5 ton/fad.

Table 7. Biological, seed and straw yields (ton/fad) as well as harvest index of faba bean as affected by vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Treatment	Biological yield (ton/fad.)			Seed yield (ton/fad.)			Straw yield (ton/fad.)			Harvest index		
	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.
Vermicompost level (V)												
Without supply (V_1)	4.07 d	4.43 d	**4.25 d**	1.72 d	1.92 d	**1.82 c**	1.30 c	1.48 d	**1.39 d**	0.43 a	0.45 a	**0.44 a**
1.5 ton/fad (V_2)	4.49 c	5.01 c	**4.75 c**	1.85 c	2.04 c	**1.95 b**	1.81 b	1.95 c	**1.88 c**	0.44 a	0.43 b	**0.44 a**
3 ton/fad (V_3)	4.83 b	5.25b	**5.04 b**	2.14 b	2.41 b	**2.28 a**	1.88 b	2.10 b	**1.99 b**	0.44 a	0.46 a	**0.45 a**
4.5 ton/fad (V_4)	5.39 a	5.98a	**5.69 a**	2.26 a	2.52 a	**2.39 a**	2.12 a	2.36 a	**2.24 a**	0.42 b	0.42 c	**0.42 b**
F.test	*	*	*	*	*	*	*	*	*	*	*	*
Rhizobium strains inoculation												
Without inoculation (R_0)	4.16c	4.60 c	**4.38 c**	1.80 c	2.02 b	**1.91 b**	1.45 c	1.61 c	**1.53 c**	0.44 b	0.45 b	**0.45 b**
R. gallicum (R_1)	4.79 b	5.25 b	**5.02 b**	1.89 b	2.10 b	**1.99 b**	1.99 a	2.25 a	**2.12 a**	0.39 c	0.40 c	**0.40 c**
R. tropici (R_2)	5.15 a	5.66 a	**5.41 a**	2.29 a	2.57 a	**2.43 a**	1.89 b	2.07 b	**1.98 b**	0.46 a	0.48 a	**0.47 a**
F.test	*	*	*	*	*	*	*	*	*	*	*	*
Interaction (V × R)	*	*	*	*	*	*	*	*	*	*	*	*

* denotes Significant at 5% probability level.

Table 8. Biological, seed and straw yields (ton/fad) of faba bean as well as harvest index as affected by the interaction between vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Trait	Biological yield (ton/fad.)				Seed yield (ton/fad.)				Straw yield (ton/fad.)				Harvest index			
VC level	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4
Rhizobium	**1st season**															
R_0	3.61 k	3.98 j	4.28 h	4.78 e	1.56 h	1.67 g	1.94 e	2.04 d	1.06 f	1.48 gh	1.54 g	1.74 f	0.44 c	0.45 bc	0.45	0.43 c
R_1	4.16 i	4.59 f	4.93 d	5.50 b	1.63 g	1.76 f	2.03 d	2.15 c	1.46 he	2.03 d	2.11 c	2.38 a	0.39 de	0.40 d	0.40 d	0.38 e
R_2	4.47 g	4.93 d	5.30 c	5.92 a	1.98 e	2.13 c	2.46 b	2.60 a	1.39 e	1.93 e	2.01 d	2.26 b	0.46 ab	0.47 a	0.47 a	0.45 b
	2nd season															
R_0	3.95 k	4.47 j	4.68 h	5.33 e	1.75 h	1.86 g	2.19 e	2.29 d	1.21 h	1.59 g	1.72 f	1.93 e	0.46 b	0.44 c	0.47 b	0.43 c
R_1	4.51 i	5.10 f	5.34 e	6.08 b	1.82 g	1.93 f	2.28 d	2.38 c	1.69 f	2.23 c	2.40 b	2.70 a	0.41 de	0.39 e	0.42d	0.38 e
R_2	4.86 g	5.50 d	5.76 c	6.56 a	2.22 de	2.36 c	2.79 b	2.92 a	1.56 g	2.05 d	2.21 c	2.48 b	0.49 a	0.47 b	0.50 a	0.46 b

VC levels are vermicompost levels, R0 is un inoculation, R_1 is *Rhizobium gallicum*, R_2 is *Rhizobium tropici*, V_1 =0 ton/fad, V_2 =1.5 ton/fad, V_3 =3 ton/fad and V4 = 4.5 ton/fad.

Harvest Index

The harvest index was relatively stable across treatments but slightly lower at higher vermicompost levels (*e.g.*, V_4: 0.42 in both seasons). The highest harvest index was recorded for V_1 (0.43 and 0.45). R_2 achieved the highest harvest index (0.46 and 0.48), indicating better partitioning of dry matter toward seed production. Significant interactions were observed. The combination of $V_3 \times R_2$ produced the highest harvest index in the second season (0.50).

The slightly lower harvest index at high vermicompost levels reflects increased vegetative growth relative to seed production. R_2's ability to maximize the harvest index demonstrates its efficiency in directing assimilates toward reproductive structures, ensuring higher economic yield.

Overall, the results emphasize the complementary roles of vermicompost and Rhizobium inoculation in improving yield traits and quality of faba bean. The combination of 4.5 ton/fad of vermicompost with *Rhizobium tropici* (R_2) was the most effective treatment, highlighting the importance of integrated nutrient management strategies for sustainable agriculture.

Nitrogen content (%), N uptake (kg/fad.) and Protein Yield (%)

Results presented in Tables 9 and 10 show the significant efficacy of adding vermicompost and treating seeds by Rhizobium strains on seeds and straw N content in seeds and straw as well as N uptake; besides, the protein content obtained due to study treatments. The effect of interaction between the previous factor over the studied traits is illustrated in Tables 11 and 12.

Seeds N Content (%)

In examining the main effects of vermicompost levels (Table 9), nitrogen (N) content in seeds increased consistently with raising vermicompost applications. Starting at 2.6% with no vermicompost supply (0 ton/fad.), N content peaked at 3.1% in the first season and 3.25% in the second one at the highest level (4.5 ton/fad). Refeering to the inoculation treatments, both *Rhizobium gallicum* and *Rhizobium tropici* strains improved N content in seeds over the uninoculated treatment.

Regarding the interactive effect (Table 10), results affirmed that each raising in the vermicompost level supply was conjoined with operative increases in seeds' N content under the three inoculation treatments. With respect to the other direction of the interactive influence, inoculation with either R_1 or R_2 was effectual in raising the seeds' N content via uninoculation treatment whatever the vermicompost level supplied is, in both seasons. The highest N content (3.28% and 3.44%) in the 1st and the 2nd seasons was the resultant of the V_4 x R_1 interaction, whilst the lowest N content (2.32% and 2.30%) in the 1st and the 2nd seasons was the outcome of the V_0 x R_0 interaction.

The results suggest that both vermicompost application and *Rhizobium* inoculation significantly enhance N content in faba bean seeds. Vermicompost likely boosts soil nitrogen availability, while *Rhizobium* inoculation enhances nitrogen fixation in legume roots, translating to higher nitrogen accumulation in seeds. These findings highlight the synergy between organic fertilization and microbial inoculation in promoting nutrient-rich yields in faba beans, particularly valuable in low-input or sustainable agricultural systems.

Straw N Content (%)

For nitrogen content in straw (Table 9), similar trends were observed as with seeds N content. The main effect of increasing vermicompost doses elevated N content in straw from 1.50% (0 ton/fad) up to 1.98 % (4.5 ton/fad) as combined analysis. *Rhizobium* inoculation also positively influenced straw N content, with *R. gallicum* and *R. tropici* inoculations increasing levels compared to the control (no inoculation). The interaction effects (Table 10) revealed that the combination of *R. gallicum* inoculation with higher vermicompost doses consistently produced the highest N content in straw across seasons.

These findings indicate that both vermicompost application and *Rhizobium* inoculation contribute to greater nitrogen accumulation not only in seeds but also in straw. This suggests improved nitrogen assimilation within the plant's entire structure, beneficial for both yield quality and subsequent

Table 9. Nitrogen content in seeds and straw (%) as well as N uptake in seeds and straw (kg/fad.) of faba bean as affected by vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Treatment	Seeds N content (%)			Straw N content (%)			Seeds N uptake (kg)			Straw N uptake (kg/fad)		
	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.
Vermicompost level (V)												
Without supply (V_1)	2.60 d	2.38 d	**2.49 d**	1.42 d	1.57 c	**1.50 c**	45.65 d	44.81 d	**45.23 d**	18.62 d	23.52 d	**21.07 d**
1.5 ton/fad (V_2)	2.70 c	2.92 c	**2.81 c**	1.47 c	1.63 c	**1.55 c**	50.11 c	59.90 c	**55.01 c**	25.89 c	31.17 c	**28.53 c**
3 ton/fad (V_3)	2.93 b	3.10 b	**3.02 b**	1.65 b	1.81 b	**1.73 b**	63.58 b	75.03 b	**69.31 b**	28.67 b	35.25 b	**31.96 b**
4.5 ton/fad (V_4)	3.10 a	3.25 a	**3.18 a**	1.86 a	2.09 a	**1.98 a**	70.84 a	82.17 a	**76.51 a**	39.91 a	50.33 a	**45.12 a**
F.test	*	*	*	*	*	*	*	*	*	*	*	*
Rhizobium strains inoculation												
Without inoculation (R_0)	2.53 b	2.81 b	**2.67 c**	1.82 a	2.01 a	**1.92 a**	45.77 c	56.98 c	**51.38 c**	26.19 c	32.09 c	**29.14 c**
R. gallicum (R_1)	2.99 a	3.08 a	**3.04 a**	1.50 b	1.68 b	**1.59 b**	57.17 b	65.67 b	**61.42 b**	30.99 a	39.56 a	**35.28 a**
R. tropici (R_2)	2.98 a	2.85 b	**2.92 b**	1.48 c	1.64 b	**1.56 b**	69.70 a	73.78 a	**71.74 a**	27.63 b	33.55 b	**30.59 b**
F.test	*	*	*	*	*	*	*	*	*	*	*	*
Interaction (V × R)	*	*	*	*	*	*	*	*	*	*	*	*

* denotes Significant at 5% probability level.

Table 10. Nitrogen content in seeds and straw (%) as well as N uptake in seeds and straw (kg/fad.) of faba bean as affected by the interaction between vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Trait	N content in seeds (%)				N content in straw (%)				N uptake in seeds (kg)				N uptake in straw (kg/fad)			
VC level	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4
Rhizobium	**1st season**															
R_0	2.32 g	2.41 f	2.62 e	2.77 d	1.62 e	1.67 d	1.88 b	2.12 a	36.31 j	39.86 i	50.57 g	56.35 f	17.25 j	23.99 h	26.56 f	36.97 c
R_1	2.75 d	2.85 c	3.10 b	3.28 a	1.33 hi	1.38 g	1.55 f	1.74 c	45.36 h	49.79 g	63.17 d	70.38 c	20.41	28.38 e	31.43 d	43.75 a
R_2	2.74 d	2.84 c	3.09 b	3.26 a	1.31 h	1.36 gh	1.53 f	1.72 c	55.30 f	60.70 e	77.02 b	85.81 a	18.20 i	25.30 g	28.02 e	39.01 b
	2nd season															
R_0	2.30 h	2.82 f	2.99 e	3.14 c	1.78 e	1.85 d	2.06 b	2.37 a	39.00 l	52.13 i	65.30 g	71.51 e	21.53 k	28.53 h	32.26 f	46.07 c
R_1	2.52 g	3.09 d	3.28 b	3.44 a	1.49 h	1.55 g	1.72 ef	1.98 c	44.95 k	60.08 h	75.26 d	82.42 c	26.54 i	35.17 e	39.77 d	56.79 a
R_2	2.33 h	2.86 f	3.04 d	3.18 c	1.45 i	1.51 gh	1.68 f	1.94 c	50.50 j	67.50 f	84.55 b	92.60 a	22.51 j	29.83 g	33.73 f	48.16 b

VC levels are vermicompost levels, R_0 is un inoculation, R_1 is *Rhizobium gallicum*, R_2 is *Rhizobium tropici*, V_1 =0 ton/fad, V_2 =1.5 ton/fad, V_3 =3 ton/fad and V4 = 4.5 ton/fad.

Table 11. Total nitrogen uptake in seeds and straw (kg/fad) and protein yield as affected by vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Treatment	Total N uptake (kg/fad)			Protein yield (kg/fad)		
	2022/23	2023/24	Comb.	2022/23	2023/24	Comb.
Vermicompost level (V)						
Without supply (V_1)	64.27 d	68.32 d	**66.30 d**	239.68 d	235.24 d	**237.46 d**
1.5 ton/fad (V_2)	76.01 c	91.07 c	**83.54 c**	263.10 c	314.50 c	**288.80 c**
3 ton/fad (V_3)	92.25 b	110.28 b	**101.27 b**	333.79 b	393.92 b	**363.86 b**
4.5 ton/fad (V_4)	110.75 a	132.50 a	**121.63 a**	371.92 a	431.39 a	**401.66 a**
F.test	*	*	*	*	*	*
Rhizobium strains inoculation						
Without inoculation (R_0)	71.96 c	89.07 c	**80.52 c**	240.28 c	299.16 c	**269.72 c**
R. gallicum (R_1)	88.17 b	105.23 b	**96.70 b**	300.17 b	344.77 b	**322.47 b**
R. tropici (R_2)	97.33 a	107.33 a	**102.33 a**	365.93 a	387.35 a	**376.64 a**
F.test	*	*	*	*	*	*
Interaction (V × R)	*	*	*	*	*	*

* denotes Significant at 5% probability level.

Table 12. Total nitrogen uptake in seeds and straw (kg/fad) and protein yield of faba bean as affected by the interaction between vermicompost levels and inoculation by *Rhizobium* strains in both seasons

Trait	Total N uptake (kg/fad)				Protein yield (kg/fad)			
VC level	**V1**	**V2**	**V3**	**V4**	**V1**	**V2**	**V3**	**V4**
Rhizobium				**1st season**				
R_0	53.89 j	63.73 i	77.35 f	92.86 d	190.62 j	209.25 i	265.47 g	295.79 f
R_1	66.03 h	78.09 f	94.78 d	113.78 b	238.13 h	261.4 g	331.64 d	369.52 c
R_2	72.89 g	86.20 e	104.62 c	125.60 a	290.30 f	318.67 e	404.29 b	450.47 a
				2nd season				
R_0	60.53 h	80.68 f	97.70 d	117.38 c	204.72 i	273.70 g	342.81 e	375.42 d
R_1	71.51 g	95.32 e	115.42 c	138.68 b	235.93h	315.42 f	395.08 c	432.66 b
R_2	72.93 g	97.22 d	117.73 c	141.45 a	265.07 g	354.38 e	443.87 b	486.09 a

VC levels are vermicompost levels, R_0 is un inoculation, R_1 is *Rhizobium gallicum*, R_2 is *Rhizobium tropici*, V_1 =0 ton/fad, V_2 =1.5 ton/fad, V_3 =3 ton/fad and V_4 = 4.5 ton/fad.

soil health when crop residues are returned to the field. Enhanced N content in straw through combined organic and microbial inputs reinforces the sustainable potential of this management approach for soil fertility (**Khalid *et al.*, 2023**).

Seeds N Uptake (kg/fad.)

Results in Table 9 indicate that nitrogen uptake in seeds significantly increased with vermicompost application, with uptake starting at 45.65 kg/fad (0 ton/fad) and reaching up to 76.51 kg/fad., with 4.5 ton/fad in the combined analysis *Rhizobium* inoculation also positively affected seed N uptake, with *R. tropici* inoculation resulting in the highest N uptake in both seasons and their meta-analysis. The interaction effects presented in Table 10 show that the combined application of vermicompost at 4.5 ton/fad with *R. trpici* inoculation consistently led to the highest N uptake across both seasons.

The increase in seed N uptake with combined organic and microbial inputs underlines the effectiveness of integrating *Rhizobium* inoculants and vermicompost to maximize nutrient absorption. This approach leverages the nitrogen-fixing capabilities of *Rhizobium* strains along with the organic nutrient boost from vermicompost, which may provide a more reliable and sustainable source of nitrogen for legume crops. These results are supported by what was reported by **Fageria *et al.* (2008)**.

Straw N uptake (kg/fad.)

Straw nitrogen uptake followed a similar trend as in seeds N uptake (Table 9). The main effects of vermicompost showed that straw N uptake increased from 21.07 kg/fad., at 0 ton/fad., to 45.12 kg/fad., at 4.5 ton/fad., (pooled analysis results). Both *Rhizobium* inoculations had positive effects on straw N uptake, with the highest values achieved in the *R. gallicum* inoculation. Interaction effects highlighted that each additional level of vermicompost, especially when paired with inoculation, further elevated straw N uptake (Table 10).

The consistent increase in straw N uptake through combined treatments points to enhanced nitrogen mobilization throughout the plant structure. This outcome supports the idea that such combined treatments not only improve nutrient uptake efficiency for immediate crop needs but could also lead to greater nutrient recycling when straw is returned to the soil, thereby supporting longer-term soil health.

Total N Uptake (kg/fad.)

Total N uptake (sum of N in seeds and straw) showed substantial increases with vermicompost application (Table 11). Starting at 66.30 kg/fad., at the 0 ton/fad., level, total N uptake reached 121.63 kg/fad., with 4.5 ton/fad in the combined analysis. The *Rhizobium* treatments also showed significant main effects, with the highest total N uptake observed in *R. tropici* inoculation. Interaction effects indicated that each increase in vermicompost, combined with *R. gallicum* or *R. tropici*, maximized total nitrogen uptake across both seasons (Table 12).

The combined increase in total N uptake across vermicompost and inoculation treatments demonstrates the cumulative benefit of these treatments on nitrogen acquisition in faba beans. Higher total N uptake not only reflects improved growth and productivity but also indicates potential benefits for subsequent crops if nitrogen-rich residues are reincorporated into the soil. This holistic nitrogen management approach may be particularly useful for sustainable agriculture practices. These results are in line with **Ndakidemi *et al*. (2006) and Jensen *et al.* (2010)**.

Protein Yield (kg/fad.)

The results of protein yield (Table 11) in faba bean also benefited from increasing vermicompost applications, with protein yield rising from 237.46 kg/fad (0 ton/fad) to 401.66 kg/fad (4.5 ton/fad.) in the pooled analysis. *Rhizobium* inoculation positively impacted protein yield, with the highest yields recorded under *R. tropici* treatment. Interaction effects indicated that protein yield was optimized when higher vermicompost levels were combined with either *Rhizobium* inoculation, achieving the highest yields with *R. gallicum* (Table 12).

The observed increase in protein yield underscores the positive effects of vermicompost and *Rhizobium* inoculation on protein biosynthesis in faba beans. Enhanced nitrogen availability from vermicompost likely supports amino acid production, while *Rhizobium* inoculation further enriches nitrogen assimilation. For farmers aiming to boost legume protein content, this combination could be especially advantageous in low-input systems where enhancing crop nutritional quality is critical.

Conclusion

This study demonstrates the beneficial effects of vermicompost application and *Rhizobium* inoculation on faba bean growth, nodulation, and yield parameters. Higher levels of vermicompost (up to 4.5 ton per fad.) significantly increased nodulation, biomass, pod production, and overall seed yield. *Rhizobium tropici* was particularly effective, enhancing nodulation, pod numbers, and seed weight, while *Rhizobium gallicum* notably improved nitrogen content and the harvest index. The combined application of vermicompost and *Rhizobium* inoculants fostered nutrient-rich, high-yielding plants, underscoring the value of organic and microbial inputs in sustainable agriculture. This integrated approach optimizes nitrogen fixation, supports plant growth, and improves soil fertility, positioning it as an effective strategy for increasing legume crop productivity.

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الزراعة المستدامة للفول البلدي (*Vicia faba* L.) باستخدام الفيرمى كمبوست والبكتيريا المثبتة للنيتروجين

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تستعرض هذه الدراسة التأثيرات المشتركه لإضافة السماد الدودي (الفيرمى كمبوست) والتلقيح بالبكتيريا العقدية (الريزوبيوم) على نمو وإنتاجية الفول البلدي (*Vicia faba* L.) خلال موسمين شتويين متتاليين (2022/23 – 2023/24) في الأرض الرملية بمنطقة الخطارة – محافظة الشرقيه – جمهورية مصر العربيه. تم تقييم أربعة مستويات من السماد الدودي (0، 1.5، 3.0، و4.5 طن/فدان) وثلاثة معاملات للتلقيح بالبكتريا المثبته للنيتروجين (دون تلقيح، *R. tropici* و*R. gallicum*) باستخدام تصميم القطع المنشقه فى ثلاث مكررات. أظهرت النتائج أن إضافة السماد الدودي بمعدل 4.5 طن/فدان أدى إلى زيادة معنويه في عدد العقد البكتيرية/نبات (بمتوسط 95.19 عقدة) ووزنها الجاف (2.14 جرام في الموسم الثاني). تفوق تلقيح *R. tropici* على *R. gallicum*، حيث سجل زيادة بنسبة 17.45% في العقد البكتيرية وتحسين تثبيت النيتروجين. ارتفع طول النبات بنسبة 41.19%، وبلغ عدد الأفرع لكل نبات ذروته عند 5.31 مع الجمع بين 4.5 طن/فدان من السماد الدودي والتلقيح بـ R. tropici. شهدت مكونات المحصول استجابات معنوية لنفس المعامله السابقه (الجمع بين 4.5 طن/فدان من السماد الدودي والتلقيح بـ*R. tropici*)، حيث سجل أعلى عدد للقرون (39.65 قرن/نبات)، وأكبر عدد بذور لكل قرن (5.90)، وأثقل وزن لـ100 بذرة (92.43 جرام) تحت نفس المعاملة. بلغ المحصول البيولوجى 5.98 طن/ فدان، بينما وصل محصول البذور والقش إلى 2.52 و2.36 طن/فدان على التوالي، بزيادة تفوق 30% مقارنة بالمعاملات غير المخصبة. تم تحقيق أقصى استفادة من امتصاص النيتروجين الإجمالي وإنتاج البروتين عند 132.5 كجم/فدان و431.39 كجم/ فدان على التوالي تحت هذه المعاملات. تؤكد الدراسة على الفوائد التكميلية لاستخدام الأسمدة العضوية واللقاحات الميكروبية، مما يعزز إنتاجية الفول البلدي بطريقة مستدامة مع تحسين امتصاص النيتروجين، محتوى البروتين وخصوبة التربة.

الكلمات الإسترشادية: الفول البلدي، الفيرمى كمبوست، التلقيح بالبكتيريا العقدية، تثبيت النيتروجين، مكونات المحصول، الزراعة المستدامة.

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